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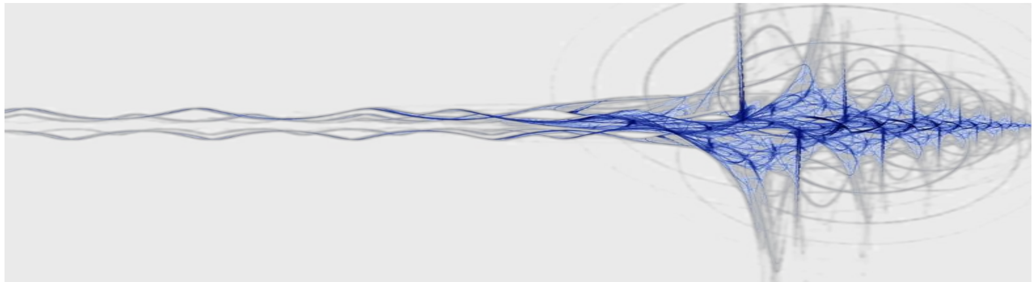

Microphonic detuning reduction in a SRF TESLA cavity using the Modified Active Disturbance Rejection algorithm: Experimental results

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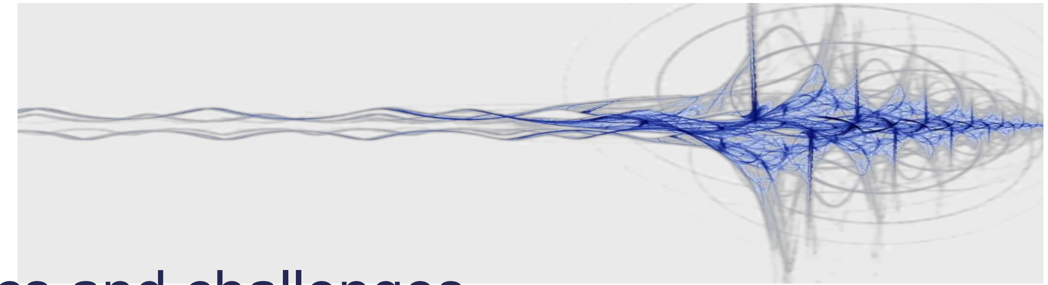
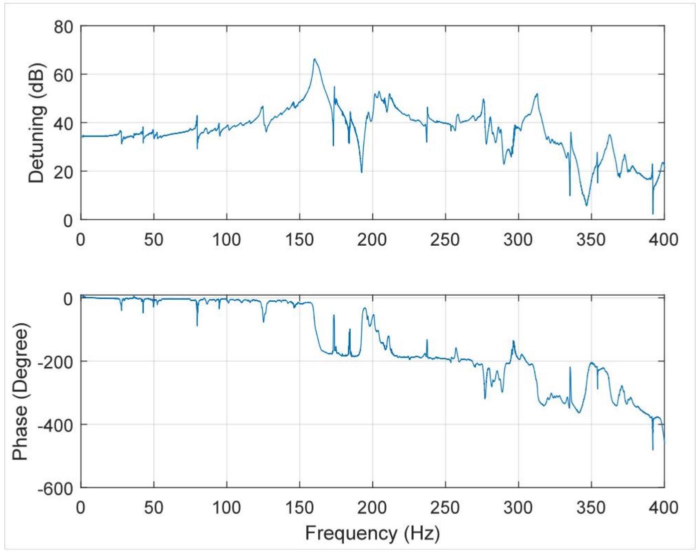


1- Target system: Characteristics and challenges



9 Cell TESLA cavity

High Q_L ($\approx 10^7$) and very narrow EM bandwidth (≈100 Hz)

Resonant frequencies within the bandwidth where perturbations influence (1-400 Hz)

Big resonant peak at 160 Hz which generates a step in the phase of almost 180 degrees (low relative stability)

Nonlinearities such as Lorentz forces, hysteresis on the piezos and ponderomotive effects

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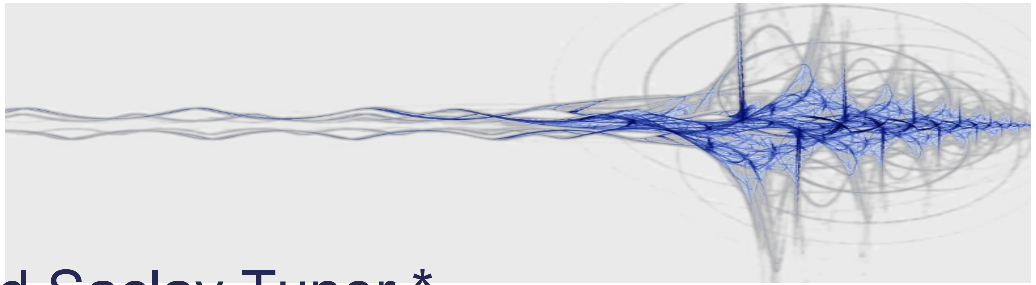


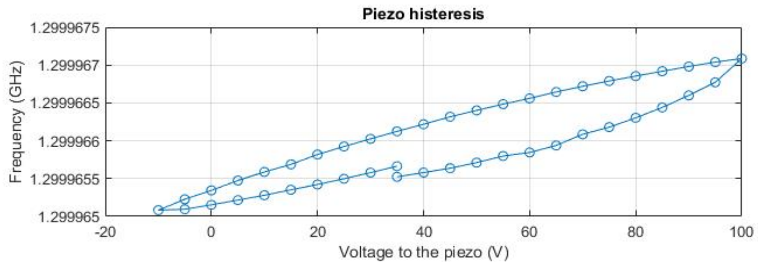
1- Target system: Piezo assisted Saclay Tuner *

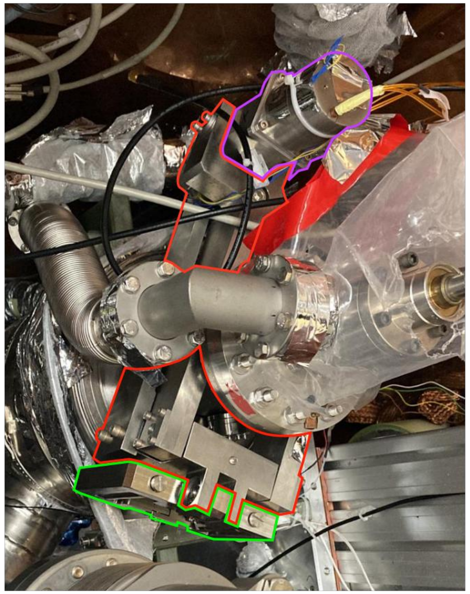
Based in a lever mechanism (Red)

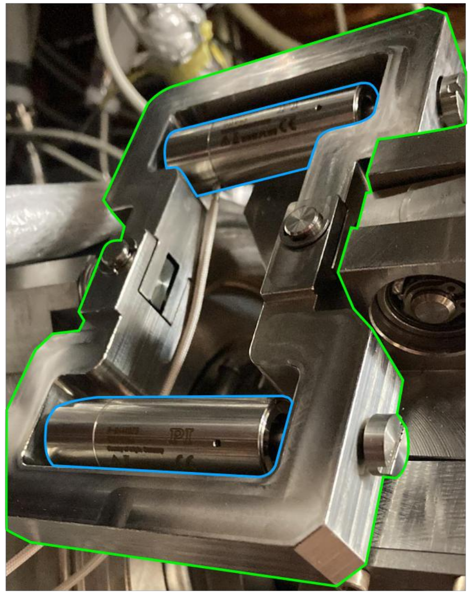
- A stepping motor (Purple) is used to correct slow or static detuning (Fabrication tolerances, Lorenz forces in CW operation etc.)
- Two Piezo actuators (Blue) mounted in a piezo holder frame (Green) are used to correct dynamic detuning.

Piezo tuner Characteristics

- Time delay = 1.2 ms
- Dynamic range = ± 100 V
- Sensitivity = 4 Hz/V







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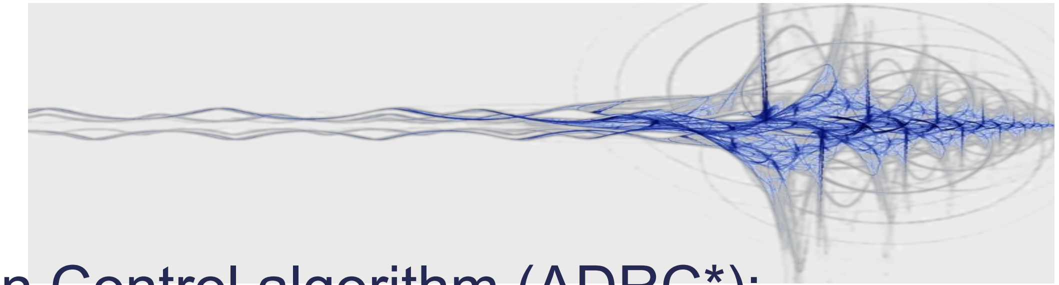
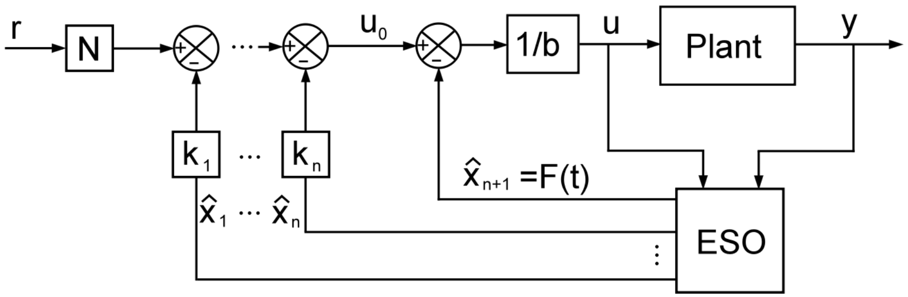
* Y. Pischalnikov and C. Contreras-Martinez, Review of the application piezoelectric actuators for srf cavity tuners, arXiv preprint arXiv:2305.06868 (2023).



2- Active Disturbance Rejection Control algorithm (ADRC*): Advantageous characteristics



Its design is almost independent from the system to control

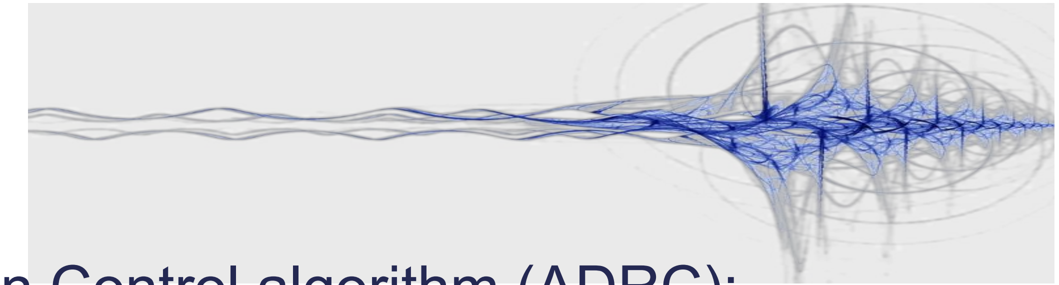
Good performance controlling nonlinear systems

Excellent disturbance rejection capabilities

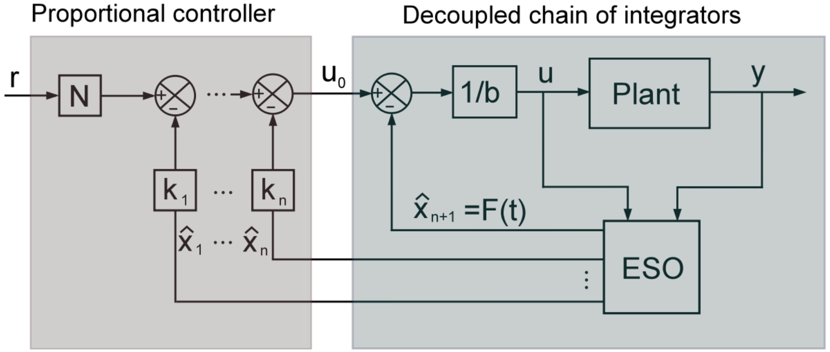
Easy to implement

Has been succesfully implemented in a large range of industrial applications

* J. Han, From pid to active disturbance rejection control, IEEE transactions on Industrial Electronics 56, 900 (2009).



2- Active Disturbance Rejection Control algorithm (ADRC): Working principle



Reduction of the plant to a decoupled chain of integrators

- Almost every system can be forced to behave like a decoupled chain of integrators via the right feedback law
- That canonical form can be easily controlled via proportional gains

$$\begin{cases}\dot{x} = f(x,t) + g(x,t)u \\ y = h(x,t)\end{cases} \xrightarrow{\text{Feedback law}} \begin{cases}\dot{x}' = Ax' + Bu \\ y = Cx'\end{cases}$$

$$A = \begin{pmatrix} 0 & 1 & 0 & \cdots & 0 \\ 0 & 0 & 1 & \cdots & 0 \\ \vdots & \vdots & \vdots & \ddots & \vdots \\ 0 & 0 & 0 & \cdots & 1 \\ 0 & 0 & 0 & \cdots & 0 \end{pmatrix}_{n \times n} \quad B = \begin{pmatrix} 0 \\ \vdots \\ 0 \\ b \end{pmatrix}_{n \times 1} \quad C = \begin{pmatrix} 1 & 0 & \cdots & 0 \end{pmatrix}_{1 \times n}$$

n stands for the relative order of the plant (difference between the number of poles and zeros)

Dynamic linearization via the technique of the observer

- Every dynamic that is different from the desired canonical form is treated as a "total disturbance" F(t)
- F(t) is estimated online via an extended state observer (ESO)
- F(t) is fed back into the system in order to force it to behave like a decoupled chain of integrators

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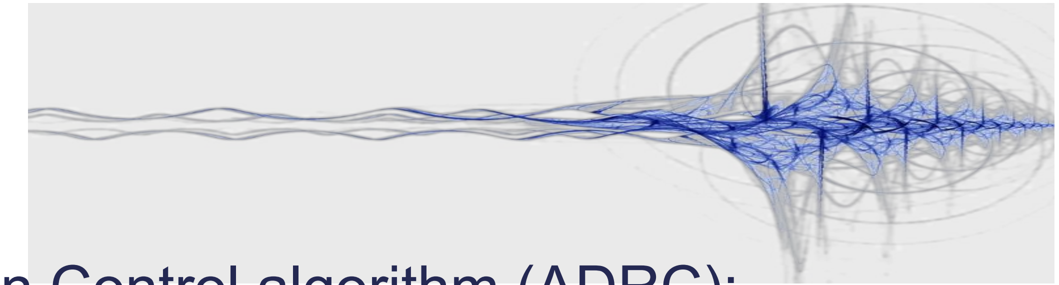


2- Active Disturbance Rejection Control algorithm (ADRC): Extended State Observer (ESO)

Extended system

- The system is extended with an extra state in order to isolate in it any internal dynamic that we dont want and any external perturbation

$$\begin{cases} \dot{x}_1 = x_2 \\ \dot{x}_2 = x_3 \\ \quad \vdots \\ \dot{x}_n = f(x_1, x_2, \dots, x_n, \omega(t), t) + bu \\ \ y = x_1 \end{cases}$$

Any unwanted internal dynamics + external perturbations (they can be unknown)

$$x_{n+1} = f(x_1, x_2, \dots, x_n, \omega(t), t) = \mathrm{F(t)}$$

$$\begin{cases} \dot{x}_1 = x_2 \\ \dot{x}_2 = x_3 \\ \quad \vdots \\ \dot{x}_n = x_{n+1} + bu \\ \dot{x}_{n+1} = F(t) + bu \\ \ y = x_1 \end{cases}$$

Decoupled chain of integrator

n stands for the relative order of the plant

Extended State Observer

- It is a Luenberger observer applied to the extended system

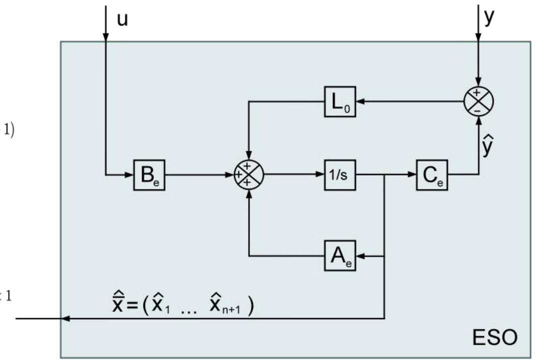
$$\begin{cases} \dot{\hat{\boldsymbol{x}}} = A_e \hat{\boldsymbol{x}} + B_e u + L_0 (y - \hat{y}) \\ \hat{y} = C_e \hat{\boldsymbol{x}} \end{cases}$$

- L_0 Defines the dynamic of the observer

$$A_e = \begin{pmatrix} 0 & 1 & 0 & \cdots & 0 \\ 0 & 0 & 1 & \cdots & 0 \\ \vdots & \vdots & \vdots & \ddots & \vdots \\ 0 & 0 & 0 & \cdots & 1 \\ 0 & 0 & 0 & \cdots & 0 \end{pmatrix}_{(n+1) \times (n+1)}$$

$$B_e = \begin{pmatrix} 0 \\ \vdots \\ 0 \\ b \\ 0 \end{pmatrix}_{(n+1) \times 1} \qquad L_0 = \begin{pmatrix} \beta_0 \\ \vdots \\ \beta_{n-1} \\ \beta_n \\ \beta_{n+1} \end{pmatrix}_{(n+1) \times 1}$$

$$C_e = \begin{pmatrix} 1 & 0 & \cdots & 0 \end{pmatrix}_{1 \times (n+1)}$$



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3- Modified Active Disturbance Rejection Control algorithm (MADRC*): General look

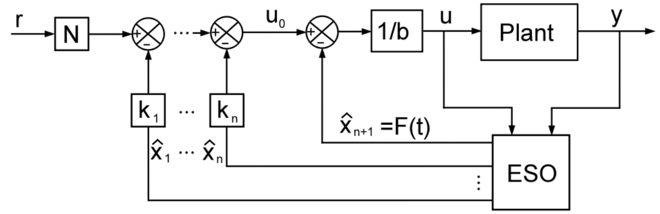
Main problem with the ADRC

- Very sensitive to time delay!!

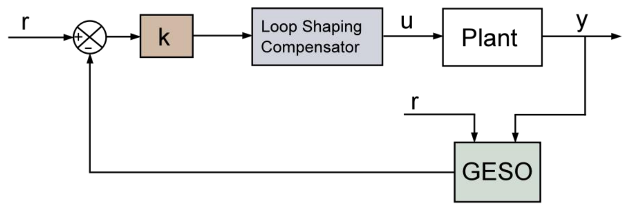
Novel MADRC

- Main idea: Open loop frequency response analisis and system stabilization through loop shaping techniques
- The scheme is redefined in order to take out the ESO from the direct chain, creating the Generalized Extended State Observer
- An adjustable gain K, and a loop shaping compensator are integrated in the direct chain in order to manipulate the open loop frequency response

Original ADRC



Novel MADRC



*J. Jugo, A. Elejaga, and P. Echevarria, Modified active disturbance rejection control scheme for systems with time delay, IET Control Theory & Applications (2023)

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3- Modified Active Disturbance Rejection Control algorithm (MADRC): GESO

Mathematical definition

- The state space controller and the total disturbance is fed back directly into the ESO

$$\begin{cases} \dot{\hat{\boldsymbol{z}}} = A_g \hat{\boldsymbol{z}} + B_g \begin{bmatrix} r \\ y \end{bmatrix} \\ y_g = K_g \hat{\boldsymbol{x}} \end{cases}$$

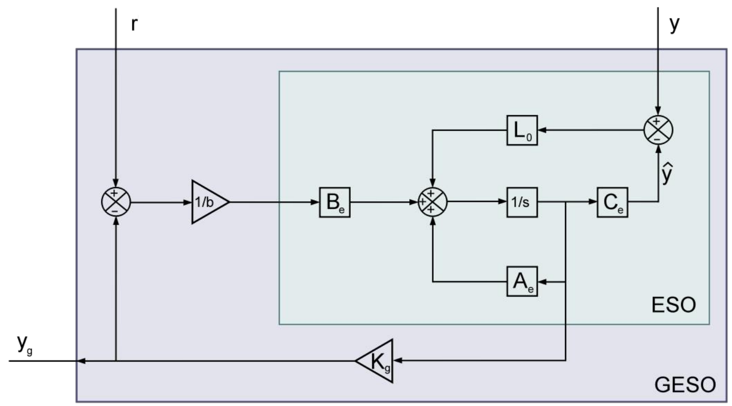
- where:

$$\mathbf{A}_g = \mathbf{A}_e - \mathbf{L}_0 \mathbf{C}_e - \frac{1}{b} \mathbf{B}_e \mathbf{K}_g = \begin{pmatrix} -\beta_1 & 1 & 0 & \cdots & 0 & 0 \\ -\beta_2 & 0 & 1 & \cdots & 0 & 0 \\ \vdots & \vdots & \vdots & \ddots & \vdots & \vdots \\ -\beta_{n-1} & 0 & 0 & \cdots & 1 & 0 \\ -\beta_n - k_1 & -k_2 & -k_3 & \cdots & -k_n & 0 \\ -\beta_{n+1} & 0 & 0 & \cdots & 0 & 0 \end{pmatrix}_{(n+1)\times(n+1)}$$

$$\mathbf{K}_g = (k_1, k_2, \ldots, k_n, 1)_{1\times(n+1)}$$

$$\mathbf{B}_g = \left(\tfrac{1}{b}\mathbf{B}_e \quad \mathbf{L}_0\right) = \begin{pmatrix} 0 & \beta_1 \\ \vdots & \vdots \\ 1 & \beta_n \\ 0 & \beta_{n+1} \end{pmatrix}_{(n+1)\times 2}$$

Mathematically identical to the original ADRC, just a redefinition of the scheme



Advantages of the GESO

- The gain of the system for high frequencies (b) is not needed anymore
- More compact and easier to implement form
- Enables the analisis of the open loop response of the system

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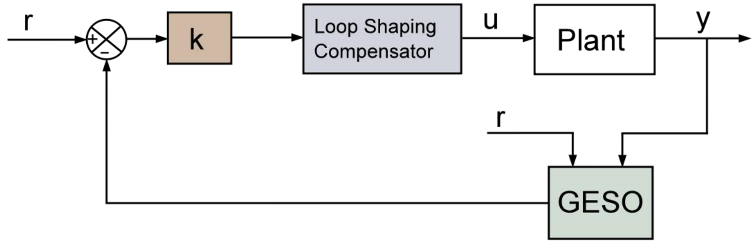
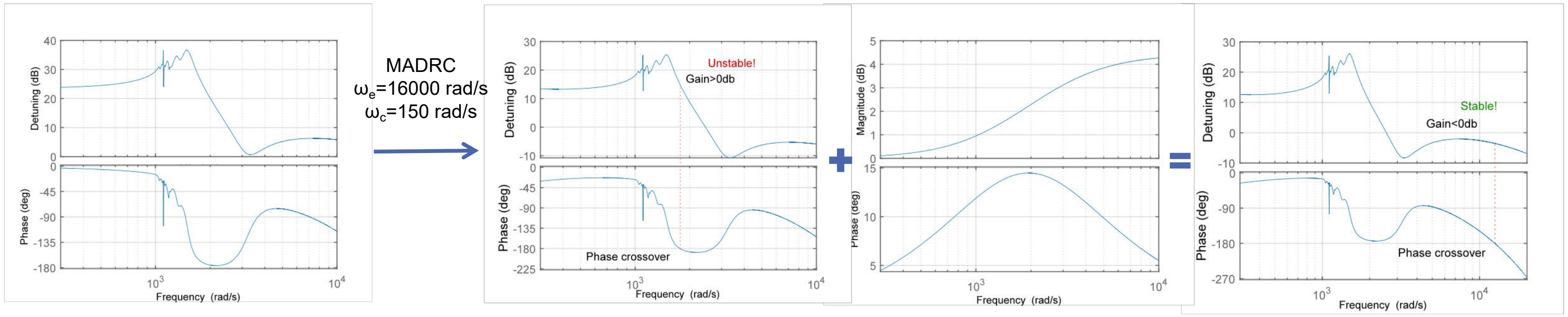
3- Modified Active Disturbance Rejection Control algorithm (MADRC): System stabilization by Loop Shaping

Function of K and the loop shaping compensator

- By modifiying K and introducing a loop shaping compensator we can tweak the phase and gain of the system in the desired frequency ranges in order to enhance the stability margin of the system
- The Loop Shaping Compensator can be created by a wide range of controllers and filters, depending on the plant to control



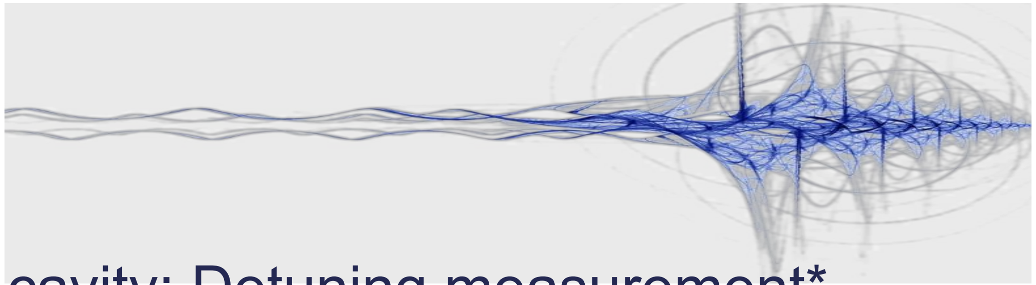


Model of a piezo tuner with 150 μs time delay

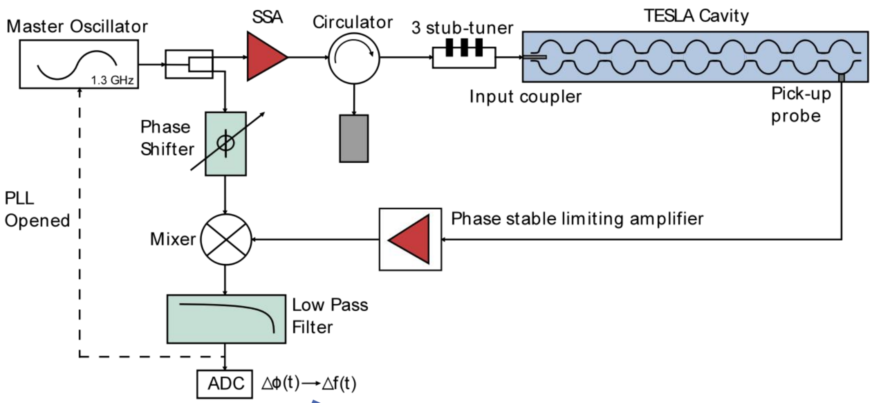
Open loop of the piezo+MADRC

Lead compensator

Open loop of the piezo+MADRC+lead



4- Real testing with the TESLA cavity: Detuning measurement*



$$\Delta f(t) = \frac{f_0}{2Q_L} tan[\Delta\Phi(t)]$$

- A tuneable master oscilator drives the cavity at 1.3 GHz
- The forward wave signal from this source is split to create a signal path for phase error measurement
- The RF signal is amplified by a Solid State Amplifier (SSA)
- By adjusting the variable penetration depth of the TTF-III input coupler antenna into the beam pipe coupler port, the coupling strength can be varied from $5 \cdot 10^6$ to $2 \cdot 10^8$
- The transmitted power signal is extracted with a weak coupling pick up antenna
- The transmitted power signal undergoes amplification using a phase-stable limiting amplifier to eliminate amplitude variations
- The phase shift is measured by a low-noise RF mixer
- Any phase offsets introduced by the RF cabling can be compensated using a phase shifter in the reference signal path

*A. Neumann, W. Anders, O. Kugeler, and J. Knobloch, "Analysis and active compensation of microphonics in continuous wave narrow-bandwidth superconducting cavities," Phys. Rev. Spec. Top.–Accel. Beams 13, 082001 (2010).

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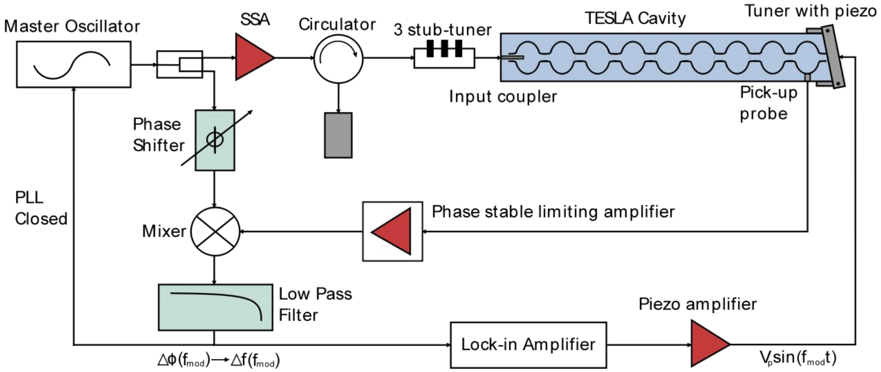
4- Real testing with the TESLA cavity: System identification

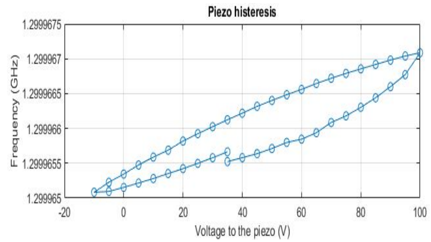


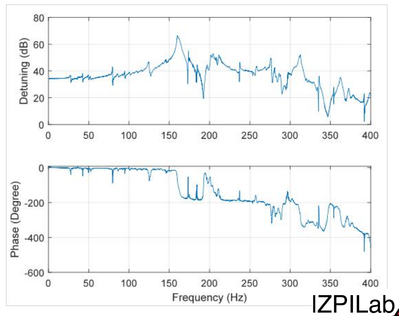
Measuring setup

- The control loop is closed with a PLL so the injected RF signal is always tuned with the cavity
- The PLL approximates the detuning comparing the phase of the incident and transmitted RF signals and corrects the forward signal's frequency so the cavity is always tuned
- A lock-in amplifier generates a ref. signal with which the cavity is exited
- The measured detuning is passed to the lock in amplifier in order to make a low noise measurement

Measurements

- A voltage sweep is performed to characterize the static response of the piezo
- A frequency sweep is performed between 0 and 800 Hz, with a step of 0.2 Hz to characterize the piezo+cavity system (time delay=1.2 ms)





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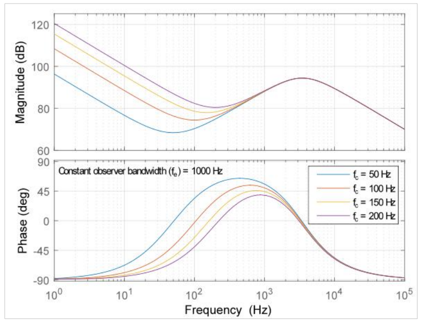
4- Real testing with the TESLA cavity: Controller design

Objective

- The objective of the controller is to reduce stochastic detuning as much as possible in the maximum possible bandwidth

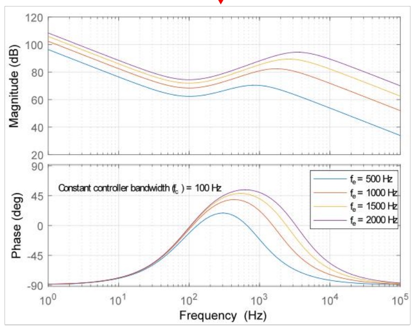
Effect of the controller bandwidth

- f_c ↑ ➡ • Disturbance rejection at low f ↑ • Stability ↓



Effect of the ESO bandwidth

- f_e ↑ ➡ • Disturbance rejection at high f ↑ • Stability ↓



A compromise between performance and relative stability is needed !

Designed controller

- GESO ➡ f_c= 170 Hz, f_e= 2000 Hz

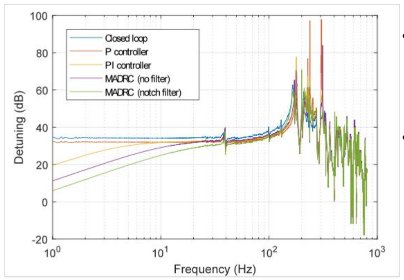
This controller is stable until K= 6.6*10^{-4}
Then, it gets unstable at 170 Hz

- Loop Shaping Compensator ➡ Notch filter centered in 170 Hz

$$H_{notch} = \frac{s^2 + 1140926}{s^2 + 854s + 1140926}$$

With the notch applied we were able to increase the gain to K=77*10^{-4}

Simulation results



- MADRC shows superior performance to more common controllers such as P and PI
- The notch filter gives the controller greater stability margin, allowing for increased gain and improved performance

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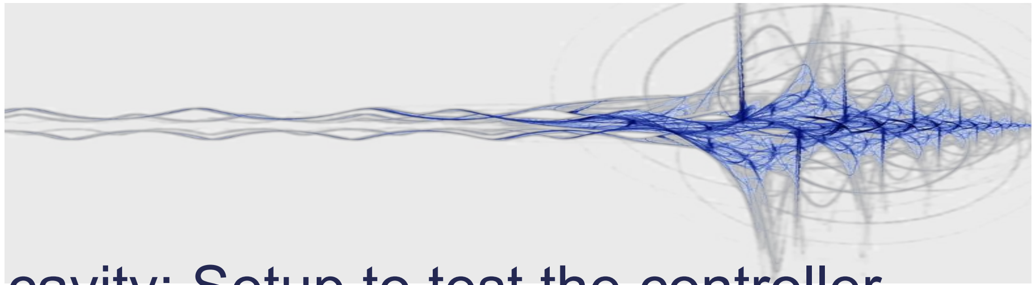
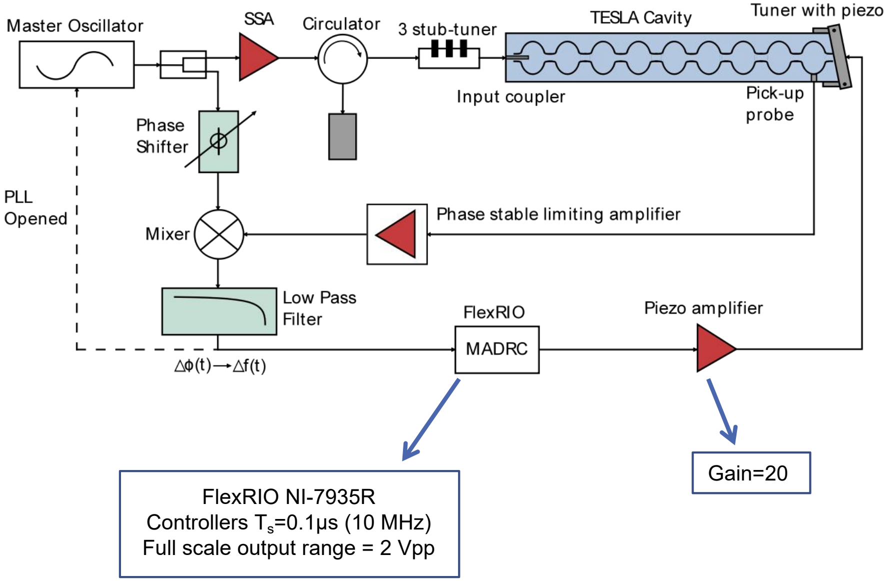


4- Real testing with the TESLA cavity: Setup to test the controller



Experimental setup

- The PLL operates in open loop: It is only used to approximate the detuning and not to control the RF signal
- The controller closes the loop so the detuning is controlled mechanically by the piezo tuners
- The cavities Q_L is fixed at 10^7 and a constant 1.3 GHz and 400 W RF signal is sent into the cavity generating a 5 MV/m field gradient
- The cavity is excited with a 11.4 Hz mechanical perturbation created by one of the piezo tuners, to mimic a low frequency constant perturbation that could be created by rotatory machinery
- The controller tries to correct the detuning generated by the constant perturbation and external disturbances

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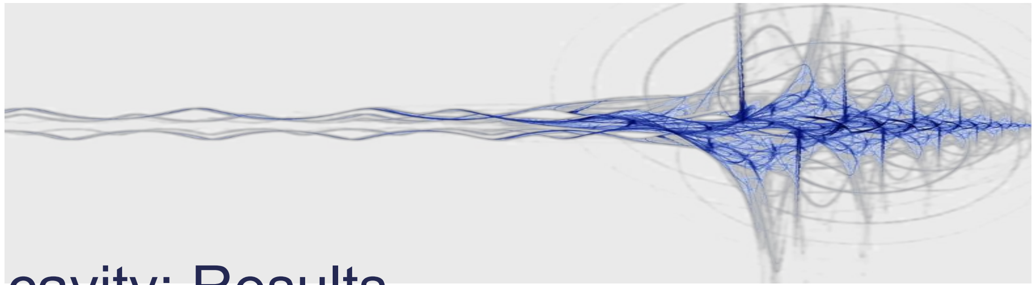
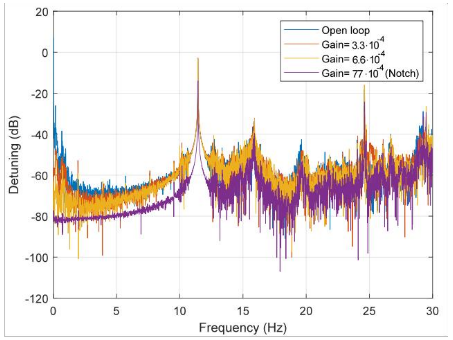
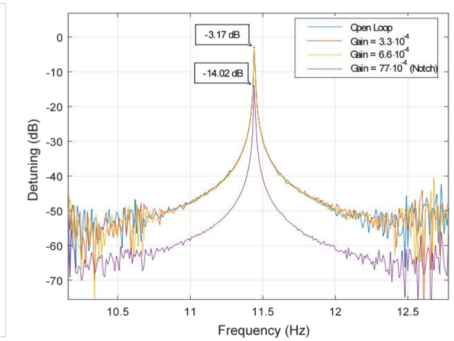
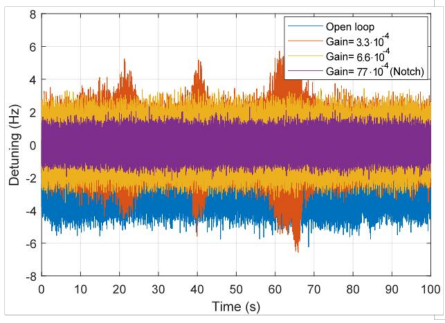
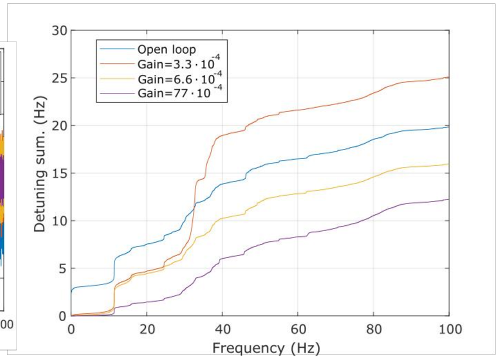


4- Real testing with the TESLA cavity: Results









Gain(10^{-4})	Peak value(Hz)	RMS(Hz)	Bandwidth(Hz)
Open loop	6.2424	2.5877	—
3.3	7.2179	1.4824	3
6.6	3.5389	1.2264	7
77	2.3252	0.5297	29

Experimental results

- As predicted in sumulation, the higher the gain K, the better the performance of the controller
- The Notch filter helped to stabilize the system and alowed us to increase the gain K in more than a decade: from $6.6*10^{-4}$ to $77*10^{-4}$
- We were able to reach a bandwidth of 29 Hz, reducing the peak detuning by a factor of 3 and the RMS by a factor of 5

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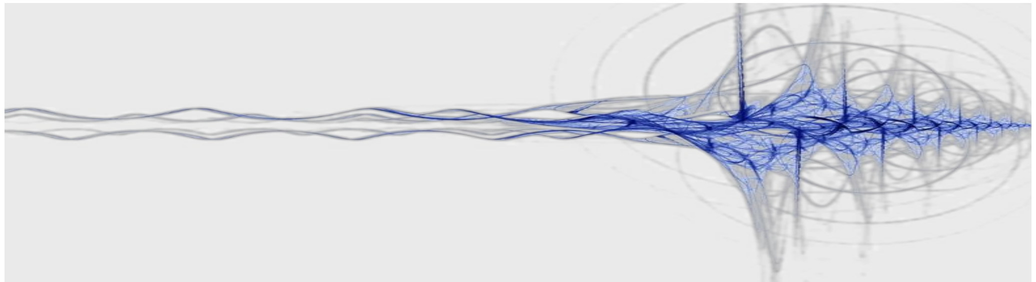

5- Conclusions

- According to the results, the MADRC structure and the designing philosophy that we developed works, offering a straight forward designing method for microphonic controllers
- When trying to mechanically control a SRF cavity, there is a physical limit that is very hard to overcome for any controller
- It may be necessary to add additional control elements, such as adaptive feedforward, in order to control frequency constant perturbations.
- We suspect that some perturbations may be unreachable for our control system, and it may be an interesting to study that phenomenon in future investigation

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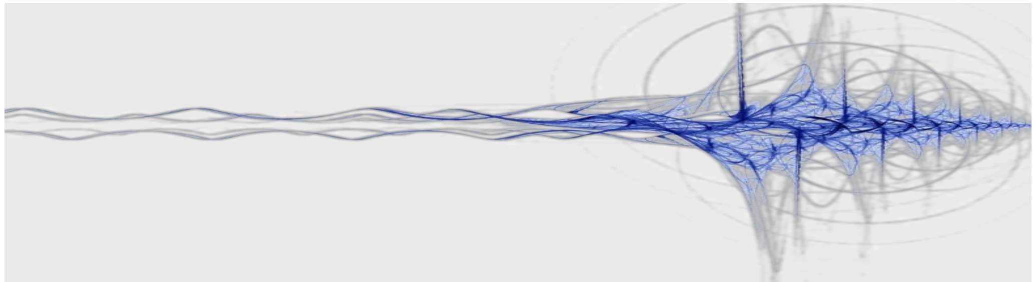

THANK YOU FOR YOUR ATTENTION

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